

# Production of antimatter in the galaxy

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**Abstract.** The astronomical dark matter could be made of weakly interacting massive species whose mutual annihilations should produce antimatter particles and distortions in the corresponding energy spectra. The propagation of cosmic rays inside the Milky Way plays a crucial role and is briefly presented. The uncertainties in its description lead to considerable variations in the predicted primary fluxes. This point is illustrated with antiprotons. Finally, the various forthcoming projects are rapidly reviewed with their potential reach.

## 1. Cosmic ray propagation throughout the Milky Way

Supersymmetric neutralinos or Kaluza–Klein particles could explain the dark matter that is indirectly observed around galaxies, inside their clusters and on cosmological scales. These species are hunted for by several experimental collaborations. As they annihilate inside the Milky Way halo, they produce high-energy cosmic rays and in particular antimatter particles such as antiprotons, antideuterons and positrons. These are rare elements which are already manufactured inside the galactic disk through the spallations of primary cosmic rays on the interstellar gas. That conventional process provides the natural background inside which the DM induced antimatter signature may be buried and whose spectral distortions could reveal an exotic signal. It is therefore crucial to derive as precisely as possible the energy spectra of the various antimatter species irrespective of the production mechanisms and to evaluate how well they are known. To reach that goal, a precise understanding of cosmic ray propagation is mandatory. We briefly sketch here how that propagation is understood and how well it is modeled.

Interstellar nuclei are accelerated by the passage of supernovae induced shock waves. The sources for primary cosmic ray nuclei are therefore located inside the disk of the Milky Way. Primaries propagate then inside the galactic magnetic fields and undergo collisions on its irregularities – the Alfvén waves. This motion is described in terms of a diffusion process whose coefficient  $K(E) = K_0 \beta \mathcal{R}^\delta$  increases with the rigidity  $\mathcal{R}$  of the cosmic ray particle as a power law. Because the scattering centers move with a velocity  $V_a \sim 20$  to  $100 \text{ km s}^{-1}$ , a second order Fermi mechanism yields some diffusive reacceleration whose coefficient  $K_{EE}$  may be expressed as

$$K_{EE} = \frac{2}{9} V_a^2 \frac{E^2 \beta^4}{K(E)} . \quad (1)$$

Ionization, adiabatic and Coulomb energy losses must also be taken into account through the energy loss rate  $b^{\text{loss}}(E)$ . Finally, galactic convection could wipe cosmic rays away from the disk

with a velocity  $V_C \sim 5$  to  $15 \text{ km s}^{-1}$ . The number of particles per unit of volume and space  $\psi = dn/dE$  may be derived from the master equation

$$V_C \partial_z \Psi - K \Delta \Psi - \partial_E \left\{ b^{\text{loss}}(E) \Psi + K_{EE}(E) \partial_E \Psi \right\} = q , \quad (2)$$

that applies for any cosmic ray species – primary or secondary – as long as the various production processes are appropriately described in the rate  $q$ . That general scheme may be implemented either numerically [1, 2] or semi-analytically through the two-zone model discussed in [3].

The latter method allows an easier derivation of the theoretical uncertainties associated to the various parameters at stake – namely  $K_0$ ,  $\delta$ ,  $V_a$ ,  $V_C$  and the thickness  $L$  of the confinements layers that extend above and beneath the Milky Way disk. The space of these propagation parameters has been extensively scanned [3] in order to select the allowed regions where the predictions on B/C – a typical CR secondary to primary ratio – match the observations. Tens of thousands of propagation models have survived that crucial test. The diffusion parameters are indeed still largely undetermined contrary to what is generally believed in our community. Recently, the same conclusion has been independently reached [4] with the help of a fully numerical code [1] in which the convective wind  $V_C$  increases linearly with vertical height  $z$ . However, the B/C ratio could not be accounted for when galactic convection and diffusive reacceleration were both implemented at the same time.

## 2. The various antimatter backgrounds and signals

### 2.1. Antiprotons

Secondary antiprotons are produced through the spallations of cosmic ray protons on the interstellar material

$$p(\text{CR}) + H(\text{ISM}) \rightarrow \bar{p} + X . \quad (3)$$

The corresponding source rate may be expressed as

$$q_{\bar{p}}^{\text{sec}}(r, E_{\bar{p}}) = \int_{E_{\bar{p}}^0}^{+\infty} \frac{d\sigma_{pH \rightarrow \bar{p}}}{dE_{\bar{p}}} \{E_p \rightarrow E_{\bar{p}}\} n_H v_p \psi_p(r, E_p) dE_p , \quad (4)$$

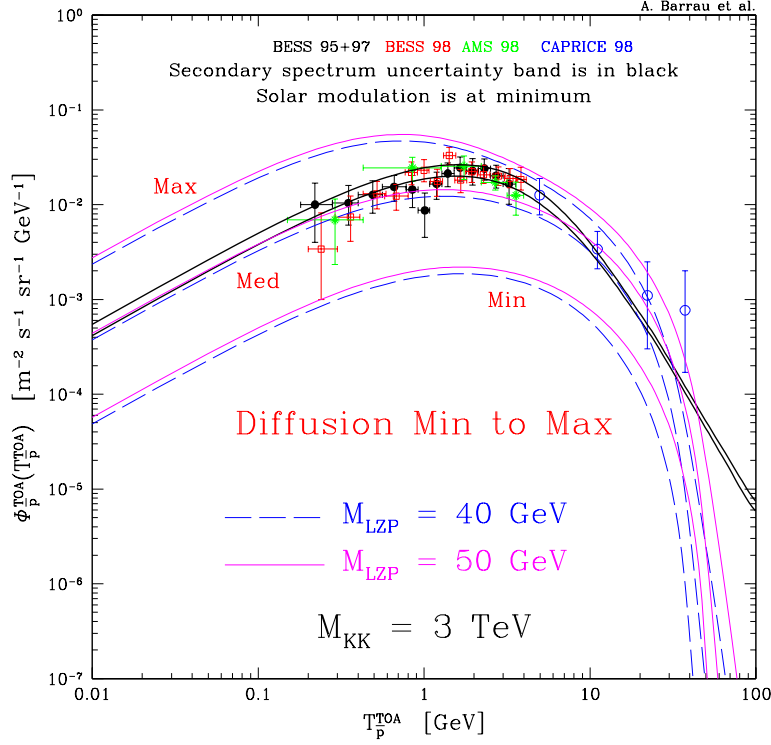
and can easily be modified in order to incorporate heavier nuclei. The top-of-atmosphere antiproton flux has been derived [7] for each of the numerous propagation models that are compatible with the B/C measurements [3]. In spite of the above-mentioned large uncertainties on the propagation parameters, the predictions all lie within the two solid black lines of Figures 1 and 2 and are in good agreement with the observations – a conclusion that has also been reached in [4] where a slightly larger uncertainty band is nevertheless obtained. The estimate of the energy spectrum of secondary antiprotons is therefore quite robust and does not depend much on the numerous and poorly known parameters that account for cosmic ray galactic propagation. Actually since boron and secondary antiprotons both originate from the same production site – Milky Way disk – it is not surprising if the former species constrains the latter.

On the contrary, primary antiprotons are produced by the mutual annihilations of DM particles

$$\chi + \chi \rightarrow q + \bar{q} , W^+ + W^- , Z^0 + Z^0 , H + H \rightarrow \bar{p} + X , \quad (5)$$

that take place all over the Milky Way DM halo, in a region that encompasses the above-mentioned confinement layers whose thickness  $L$  is still unknown. As a result, the production of primary antiprotons whose rate may be expressed as

$$q_{\bar{p}}^{\text{DM}}(r, E_{\bar{p}}) = \frac{1}{2} \langle \sigma_{\text{ann}} v \rangle \frac{dN_{\bar{p}}}{dE_{\bar{p}}} \left\{ \frac{\rho_{\chi}(r)}{m_{\chi}} \right\}^2 , \quad (6)$$



**Figure 1.** When the diffusion parameters are varied over the entire domain that is compatible with the B/C ratio, antiproton primary fluxes span two orders of magnitude whilst the secondary component lies within a much narrower band. The case of a resonant LZP [5] has been featured here [6] with  $M_{\text{LZP}} = 40$  – blue dashed – and  $50$  GeV – solid magenta. A canonical isothermal DM distribution has been assumed. In the case of minimal diffusion, the LZP signal is well below the background.

suffers from large uncertainties. Predictions span a range of  $\sim$  two orders of magnitude at low energy [8, 6]. This crucial point is illustrated in Figure 1 where the case of a resonant LZP is featured for the maximal, median and minimal configurations of table 1. Another source of

**Table 1.** Astrophysical parameters of the cosmic ray galactic propagation models giving the maximal, median and minimal primary antiproton fluxes compatible with B/C analysis [8].

case	$\delta$	$K_0$ [kpc <sup>2</sup> /Myr]	$L$ [kpc]	$V_c$ [km/sec]
max	0.46	0.0765	15	5
med	0.70	0.0112	4	12
min	0.85	0.0016	1	13.5

uncertainty is related to the DM distribution itself  $\rho_\chi(r)$  whose radial profile is generically given by

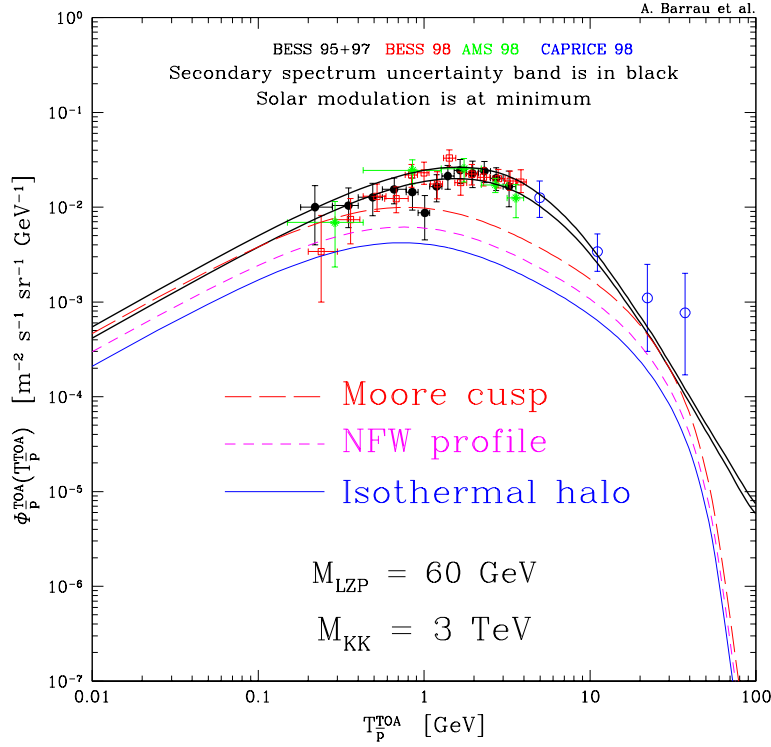
$$\rho_\chi(r) = \rho_{\text{DM}\odot} \left\{ \frac{r_\odot}{r} \right\}^\gamma \left\{ \frac{1 + (r_\odot/a)^\alpha}{1 + (r/a)^\alpha} \right\}^{(\beta-\gamma)/\alpha}. \quad (7)$$

The distance of the Solar System from the galactic center is  $r_{\odot} = 8$  kpc. The local – Solar System – DM density has been set equal to  $\rho_{\text{DM}\odot} = 0.3 \text{ GeV cm}^{-3}$ . In the case of the pseudo-isothermal profile, the typical length scale  $a$  is the radius of the central core. The profile indices  $\alpha$ ,  $\beta$  and  $\gamma$  of the dark matter distributions which have been considered in Figure 2 are indicated in table 2. Notice finally that the halo could be clumpy so that the DM species annihilations

**Table 2.** Dark matter distribution profiles in the Milky Way.

Halo model	$\alpha$	$\beta$	$\gamma$	$a$ [kpc]
Cored isothermal [9]	2	2	0	4
Navarro, Frenk & White [10]	1	3	1	25
Moore [11]	1.5	3	1.3	30

could be enhanced by a boost factor that is still very uncertain.



**Figure 2.** The effect of the DM halo profile is presented [6] in this figure where the mass of the LZP [5] has been set equal to  $M_{\text{LZP}} = 60 \text{ GeV}$  with a Kaluza–Klein scale  $M_{\text{KK}}$  of 3 TeV. The more divergent and concentrated the LZP distribution at the center of the Milky Way, the larger the antiproton yield. That effect is particularly acute in this plot where maximum diffusion parameters have been assumed.

Constraining the MSSM parameter space or deriving informations on Kaluza–Klein particles from antiproton measurements may turn out to be tricky. However in the case of light neutralinos whose relic density accounts for the WMAP measurement, stringent limits may be extracted. In

particular should  $L$  exceed 3 kpc, a neutralino lighter than 40 GeV would be basically excluded – see [12] for details.

### 2.2. Antideuterons

Secondary antideuterons are manufactured by CR nuclei spallations in which an antiproton–antineutron pair is produced and then merges. This fusion is a very rare event because two antinucleons must be produced at the same time and the difference between their momenta must not exceed  $P_{\text{coal}}$ . The typical value that has been derived in [13] and used in [14] for that coalescence momentum is  $P_{\text{coal}} = 58$  MeV. Because antideuterons are easily destroyed when they interact – their binding energy is only 2.2 MeV – they should not a priori undergo inelastic and non–annihilating scattering. In the case of antiprotons, that reaction is very efficient and flattens the spectrum at low energy – hence the difficulty to disentangle a primary signal from the secondary background. But in the case of antideuterons, that process has been assumed until recently to be negligible. If so, the secondary antideuteron spectrum exhibits a deficiency at low energy as advocated in [13] and primary antideuterons should be hunted for below a kinetic energy of  $\sim 3$  GeV/n.

This point has been extensively reanalyzed recently in [15]. If actually the  $\Delta$ –resonance excitation

$$\bar{D} + p \rightarrow \bar{D} + \Delta \quad (8)$$

is forbidden on the basis of isospin conservation, the production of pions is nevertheless possible through

$$\bar{D} + p \rightarrow \bar{D} + p + n\pi . \quad (9)$$

The cross section for inelastic and non–annihilating  $\bar{D}$  interactions is therefore small but non–vanishing. This may allow a certain flattening of the spectrum in the low energy region and could weaken the relevance of antideuterons as a clear signature for DM species. An additional source of spectral flattening investigated in [15] is the production of antideuterons through the collisions of already propagating antiprotons on interstellar H and He. The threshold for manufacturing a single antineutron is just  $7m_p$  – instead of  $17m_p$  for a pair – and low energy antideuterons should be more abundant. The final conclusion reached in [15] – with a more correct value of  $P_{\text{coal}} = 79$  MeV – strengthens the case for antideuterons. Below  $\sim 1 - 2$  GeV/n, the flux of TOA secondary antideuterons does not exceed  $\sim 10^{-7} \bar{D} \text{ m}^{-2} \text{ s}^{-1} \text{ sr}^{-1} (\text{GeV/n})^{-1}$ , a typical value expected for a primary component in the case of annihilating supersymmetric neutralinos.

As a matter of fact, a detailed analysis of the detection prospects of supersymmetric dark matter in the mSUGRA framework has been performed in [16] for models whose thermal relic density is in the range favored by current precision cosmological measurements. Direct detection and searches for antideuterons were found to be the most promising signatures.

### 2.3. Positrons

Energy losses play a crucial role in the propagation of positrons. Because galactic convection and diffusive reacceleration can be disregarded, the master equation (2) simplifies into

$$-\vec{\nabla} \cdot \left\{ K(\vec{x}, E) \vec{\nabla} \Psi \right\} - \partial_E \left\{ b^{\text{loss}}(E) \Psi \right\} = q(\vec{x}, E) . \quad (10)$$

Above a few GeV, positron energy losses are dominated by synchrotron radiation in the galactic magnetic fields and by inverse Compton scattering on stellar light and on CMB photons. The energy loss rate increases with the positron energy  $\epsilon = E/1 \text{ GeV}$  as  $b^{\text{loss}}(E) = \epsilon^2/\tau_E$  where the relevant timescale is typically  $\tau_E = 10^{16}$  s. The diffusion coefficient  $K$  is assumed to be homogeneous and equal to the galactic averaged value that is used for antiprotons and antideuterons – see section 1. But if those antinuclei can originate from remote regions [17, 18]

and probe a significant portion of the Milky Way, the high energy positrons that are detected at the Earth cannot come from far away and the unknown solar neighborhood value should be preferred. Future high precision measurements on the  $^{10}\text{Be}$  to  $^9\text{Be}$  ratio will be very valuable since the former nucleus is unstable and also originates from the local bubble [19]. Equation (10) may be solved either numerically [1] or with the help of the smart trick proposed in [20] which consists in translating the positron energy  $E$  into pseudo-time. Measurements of the positron flux show evidence for a spectral excess [21, 22] at energies  $\sim 10$  GeV. That feature is hard to explain only with secondary positrons whose flux is nevertheless subject to theoretical uncertainties – especially below  $\sim 5$  GeV – as shown in [4]. Numerous analysis have been devoted to the explanation of the putative HEAT excess in terms of annihilating supersymmetric neutralinos or Kaluza–Klein species. The latter are more promising because they directly yield electron–positron pairs with a branching ratio  $\sim 20\%$ . Large values for the boost factor or for the annihilation cross section are in any case necessary.

The PAMELA [23] and AMS–02 [24, 25] missions will collect positrons up to hundreds of GeV and will bring valuable informations on the HEAT excess and on the possible presence in the Milky Way halo of DM particles. The reach of these experiments have been studied in [26] where three years of observation and a boost factor of 5 have been assumed. In the case of a bino-like neutralino which mostly produces  $b\bar{b}$  pairs, PAMELA will be sensitive to configurations down to an annihilation cross section of order a few times  $10^{-26} \text{ cm}^3 \text{ s}^{-1}$  whereas AMS–02 will lower that value by a factor of 4. If the neutralino is now a higgsino, PAMELA will be sensitive to masses up to 380 GeV and AMS–02 will improve that limit up to 650 GeV. If now the galactic DM is made of Kaluza–Klein species, that reach will become 550 GeV in the case of PAMELA and 1 TeV for AMS–02. Remember finally that – as in the case of antiprotons – these results are affected by large uncertainties related to the propagation model.

### 3. Forthcoming experiments

The forthcoming satellite missions PAMELA and AMS–02 have just been mentioned. They are compared in table 3 with the BESS–polar experiment [27]. Long duration flights around the poles where the geomagnetic shield is no longer active allow for large values of the acceptance. Below 10 GeV, the effective sensitivity of BESS–polar for low energy antiprotons will be actually 3 times larger than for PAMELA. In the same spirit, the CREAM collaboration [28] will measure the B/C ratio between 1 and  $10^3$  TeV. It aims at the determination of the index  $\delta$  that drives the energy dependence of the diffusion coefficient  $K$ . Such a measurement is mandatory in order to reduce the large uncertainties that plague the theoretical predictions on cosmic rays [29] and in particular those on the DM induced primaries. The search for antideuterons is also extremely active. A new upper limit of  $1.9 \times 10^{-4} \text{ m}^{-2} \text{ s}^{-1} \text{ sr}^{-1} (\text{GeV}/n)^{-1}$  has been derived [30] for the differential TOA flux of cosmic ray antideuterons between 0.17 and 1.15 GeV/n. A pioneering concept [31, 32] for detecting low energy antideuterons is based on their capture by atoms whose electrons are rapidly expelled. The result is an antideuteron that orbits alone around the nucleus. As it cascades towards the ground state, several well defined X–ray photons are emitted and yield a unique signature as explained by C. Hailey in this conference.

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**Table 3.** Comparison between PAMELA, BESS-polar and AMS-02 as presented in [27].

Project	PAMELA	BESS-polar	AMS-02
Flight vehicle	Satellite	long-duration balloon	ISS
Flight duration	3 years	10–20 days	3–5 years
Altitude	300–600 km	37 km (5 g cm <sup>-2</sup> )	320–390 km
Orbit	70.4°	≥ 70°S Lat.	51.7°
Acceptance	0.0021 m <sup>2</sup> sr	0.3 m <sup>2</sup> sr	0.3 m <sup>2</sup> sr
MDR (GV)	740	150	~ 1000
Particle identification	TOF/TRD/CAL	TOF/ACC	TOF/TRD/RICH/CAL
Number of helium	4 × 10 <sup>7</sup>	(1 – 2) × 10 <sup>7</sup>	2 × 10 <sup>9</sup>
Launch	December 2005	December 2004	2007

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